Experimental Studies of Vortex-Flame Interactions in an Opposed-Jet Burner

G. J. Fiechtner,[1] P.-H. Renard,[2] C.D. Carter,[1] J.R. Gord,[1] J. M. Donbar,[1] and J. C. Rolon[2]

[1]Air Force Research Laboratory, Wright-Patterson Air Force Base, OH 45433-7103, USA. G. J. Fiechtner and C. D. Carter are with Innovative Scientific Solutions, Inc., 2766 Indian Ripple Road, Dayton, OH 45440-3638, USA.
[2]Laboratoire d'Énergétique Moléculaire et Macroscopique, Combustion, École Centrale Paris, Grande Voie des Vignes, 92295 Châtenay-Malabry Cedex, France

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1. Introduction

Recent results in numerical modeling combined with experimental measurements have led to important advances in the understanding of combustion. Numerous investigations have contributed to these advances, including a particular type of study in which the interaction of a laminar, nonpremixed flame and a vortex is examined. These efforts involve repeatable, carefully controlled conditions that are highly amenable to experimental study. In recent computational calculations, Katta (Katta et al., 1998) predicted that during the interaction of a nonpremixed hydrogen-air flame and an isolated vortex, the extinction of the OH layer would occur in an annular pattern. The experiments detailed in the present paper are performed to examine, in part, the validity of this prediction. Experimental results obtained with planar laser-induced fluorescence (PLIF) of OH are used to determine regimes in which the annular extinction occurs. Particles are seeded into the flowfield and the scattering is used for digital, two-color particle-image velocimetry (PIV) measurements. Digital PIV measurements are made simultaneously with PLIF measurements of OH. Preliminary vortex-characterization results are presented.

2. Background

Numerous experimental studies of the interaction dynamics of vortices and flames have been conducted, and many of these investigations employed two-dimensional imaging to study the interaction. For premixed flame fronts, most measurements have been made using two types of flames. Hertzberg et al. (1984) and Escudie (1988) conducted an experiment in which a Karman vortex street was produced using a cylindrical rod in a cross flow of premixed gases. A V-flame was supported behind a wire positioned downstream of the rod that produced the vortex street. Planar tomographic imaging was used to study the interaction of the vortex street and the flame. A similar interaction of a Karman vortex street and a flame was investigated by Lee et al. (1993) using PLIF imaging of OH and by Nye et al. (1996) using both OH PLIF and PIV. A disadvantage of using the vortex street is the difficulty in isolating a single vortex. Samaniego (1992) developed a means of injecting an isolated line vortex through a horizontal slot in the wall of a vertical wind tunnel, and presented results on the interaction of a line vortex and a V-flame. Schleiren images of the time-dependent vortex-flame interaction along with CH emission data from the entire flame were presented. Nguyen and Paul (1996) also studied vortex-flame interactions using the Samaniego burner, reporting results of PLIF measurements of OH and CH radicals.

In a second type of study involving premixed combustion, Jarosinski et al. (1988) studied a flame that was ignited at one end of a tube of premixed gases. A vortex was injected at the other end of the tube. The interaction dynamics were then photographed using a mercury-xenon arc lamp and a rotating-drum streak camera with a rotating-disc shutter. Recently, Driscoll and co-workers produced an impressive series of papers concerning a similar vortex-flame facility in which PIV, OH PLIF, or a combination of these imaging techniques was applied (see Driscoll et al., 1994, Mueller et al., 1998, and Sinibaldi et al., 1998, and the references therein).

Nonpremixed flames have also been the subject of experimental study. Rolon and co-workers (see Renard et al., 1998a, Renard et al., 1998b, and the references therein) recently developed an apparatus in which a vortex was injected into a flame supported between the nozzles of an opposed-jet burner. Takagi and coworkers (Takagi et al., 1996; Yoshida and Takagi, 1998) performed planar Rayleigh-scattering measurements of temperature on a similar type of opposed-jet burner in which a small jet of fuel or air was injected using a micro-nozzle with an inner diameter of only 0.25 mm. Either a jet of air was injected from the air side of the diffusion flame or a jet of fuel was injected from the fuel side. Chen and Dahm (1998) developed a facility for generating a nonpremixed burning layer that wraps into a vortex ring. The facility permits experiments to be performed under conditions of both normal gravity and microgravity, allowing the study of the influence of buoyancy.

3. **Apparatus and Procedure**

The Rolon burner that is used in these experiments is described elsewhere (Renard et al., 1998a and 1998b). The flame is supported between upper and lower nozzles separated by 40 mm, each with an exit diameter of 25 mm. The fuel consists of hydrogen diluted with nitrogen and flows from the upper nozzle. Air flows from the lower nozzle. Unique to this type of apparatus is a tube with 5-mm inner diameter that is installed concentrically within the lower nozzle. This tube is attached to a cylinder that contains a piston which, in turn, is attached to an actuator. Feeding an appropriate current to the actuator causes a solenoid to force the piston upward abruptly, resulting in the emergence of a vortex from the tube. The vortex travels upward within the surrounding oxidizer flow. Vortex propagation velocities between 0.5 m/s and 10 m/s are studied. A flow of air is supplied to the vortex tube such that in the absence of a vortex, the exit velocity matches the velocity of the air from the surrounding nozzle. To minimize the impact of room-air disturbances, upper and lower guard flows of nitrogen are supported through outer nozzles, which are concentric with the respective upper and lower inner nozzles that support the flame. Flowrates corresponding to six flame conditions that are examined are summarized in Table I. Hollow spherical ceramic particles with an approximate mean diameter of 2.4 μm are introduced into the burner flows when digital PIV measurements of the vortex velocity are performed.

Table I: Flow rates (l/min) at 21.5°C and 724 mm Hg for six flame conditions. X_{H2} is volume fraction of hydrogen in nitrogen diluent.

Gas	Flame					
	A	B	C	D	E	F
H_2	2.76	3.40	4.04	4.67	5.31	5.94
N_2 Diluent	17.1	17.1	17.1	17.0	17.0	16.9
X_{H2}	0.14	0.17	0.19	0.22	0.24	0.26
Air	11.2	11.2	11.2	11.2	11.2	11.2

PLIF measurements are accomplished by exciting hydroxyl radicals at 281.3414 nm via the $R_1(8)$ transition of the (1,0) band in the A-X system. Fluorescence from the A-X (1,1) and (0,0) bands is detected at right angles using WG-295 and UG-11 colored-glass filters, a 105-mm-focal-length f/4.5 UV lens, an image intensifier, and CCD pixels that are binned in 2x2 groups, resulting in an imaged area of 25.6 x 38.4 mm^2. The bottom of the image is 0.25-mm above the surface of the lower nozzle. A color table is used with a maximum value set to 95% of the maximum signal for all images taken at a given flame condition. The low-signal color is assigned by calculating the background noise and selecting a minimum value that is two standard deviations above this level. Therefore, in cases where "extinction" of the OH layer is observed, "extinction" refers to signal levels that fall below this minimum value and are, therefore, assigned the last color in the table. All images represent the signal collected during a single laser shot, and no smoothing of the resulting images is attempted. In studies of vortex-flame interactions conducted by other investigators [see, for example, Najm et al., (1998)], LIF was applied as a marker of some other quantity such as heat release or burning rate. In the present experiments, the OH image is obtained for direct comparison with numerical computations of the OH distribution (Katta et al., 1998); therefore, no attempt is made to correlate the images with any other quantities, although it has recently been shown that the OH concentration may be a good indicator of flame extinction in this configuration (Renard et al., 1998b).

Measurements of the velocity field are carried out using digital, two-color PIV (Gogenini et al., 1998). Here, a color digital CCD with an array of 3060 x 2036 pixels is used with a magnification that results in an imaged area of 26.0 x 39.0 mm^2. The color CCD camera and the intensified CCD array are aligned using a transparent mask printed with a graduated scale. Two lasers are used, with one PIV light sheet being produced by directly doubling the output of a Q-switched Nd:YAG laser (30 mJ/pulse at the test section). The remainder of this beam is used to pump the dye laser that is frequency doubled to excite OH fluorescence. The second PIV light sheet is produced by pumping a dye laser (employing DCM laser dye) with a second frequency-doubled, Q-switched Nd:YAG laser, resulting in laser radiation at 640 nm (40 mJ/pulse at the test section). A digital delay generator is used to drive the timing of the two lasers such that the red pulses are delayed precisely with respect to the green ones.

Results and Discussion

Superimposed velocity and OH PLIF fields are shown in Figure 1. These data allow us to characterize the velocity field during particular vortex-flame interactions to aid comparison with numerical computations. In addition, the vorticity and strain fields can also be analyzed.

The PLIF images of OH shown in Figure 2 correspond to a vortex-flame (flow conditions D of Table I) interaction in which "extinction" of the OH layer is absent. Initially, the vortex creates a small dent in the flame, and this dent begins to grow. Eventually the flame nearly surrounds the advancing vortex as it approaches the upper nozzle. In the later interaction stages, the OH PLIF signal level is observed to increase by more than a factor of five over the levels observed without a vortex.

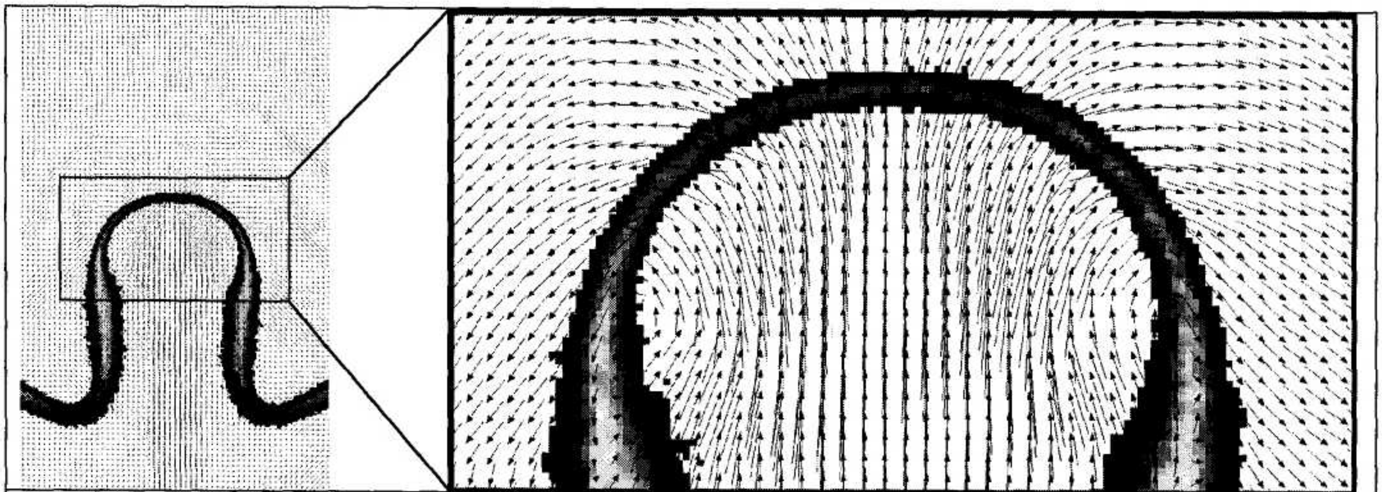

Figure 1. PLIF image of OH with superimposed two-color digital PIV vectors. Full image is shown on left (approximately 25-mm wide) with expanded cutout shown on right. The velocity field of the vortex has been severely distorted by the surrounding flame.

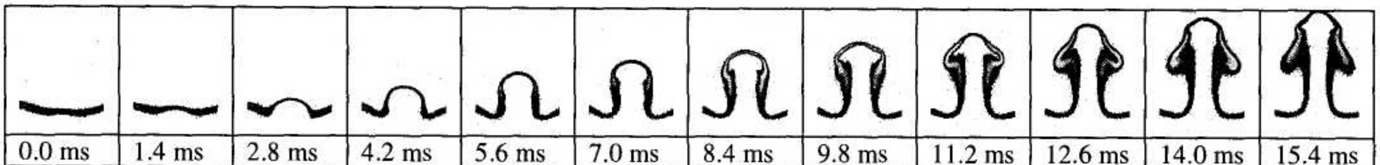

Figure 2. OH PLIF images taken when the OH layer remains intact.

The images of Figure 3 correspond to Flame E in Table I. Extinction of the OH layer takes place in an annular pattern around the sides of the vortex, leaving a burning layer at its leading edge. After extinction, the isolated island of flame burns away, and the vortex travels upward toward the other nozzle. The flame follows the vortex, traveling up the stem. As the flame overtakes the vortex, it wraps up and turns in upon itself.

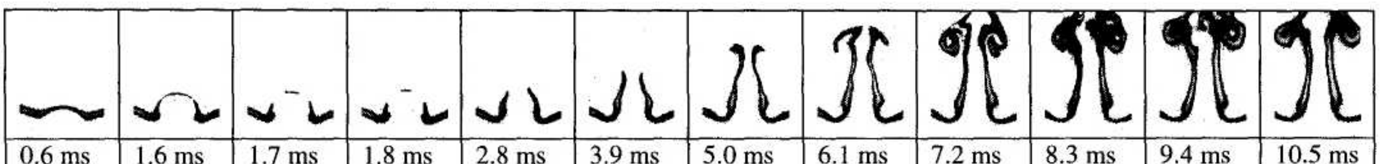

Figure 3. Sequence of images taken before and after annular ("Katta") extinction of the OH layer.

The annular decrease in the OH layer is quite similar to the experimental results of Katta (Katta et al., 1998). In fact, the numerical results were obtained before the experiments were initiated, attesting to the utility of the code. Detailed analysis of the numerical results reveal that the strain rate in the annular region is equal to or lower than that at the stagnation line, and the flame curvature increases significantly in the annular region where the break in the OH layer appears. Based on these observations, it is postulated that the annular mechanism results from the combined effect of preferential diffusion and flame curvature. Indeed, Yoshida and Takagi (1998) have found that, in nonpremixed counterflow flames of hydrogen and air into which a microjet is injected, preferential diffusion can cause enhanced H_2 concentrations in regions with concave curvature, greatly influencing extinction and reignition processes.

Conclusions

The apparatus of Rolon and co-workers (Renard et al., 1998a and 1998b and the references therein) has been implemented to study the interaction of a vortex and a flame using simultaneous PLIF measurements of OH and two-color digital PIV. An annular break in the OH layer has been observed in excellent agreement with the numerical computations of Katta (Katta et al., 1998).

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